AD 673 946

SURFACE-PARTICLE-INTERACTION MEASUREMENTS USING PADDLEWHEEL SATELLITES

Kenneth Moe, et al

Douglas Aircraft Company, Incorporated
Santa Monica, California

1968

Surface-Particle-Interaction Measurements Using Paddlewheel Satellites

Gordon S. Reiter
Space Systems Division, Hughes Aircraft Co.
El Segundo, California 90009

Kenneth Moe
Space Sciences Department, Missile & Space Systems Division
Douglas Aircraft Co., Santa Monica, California 90406

Surface-particle-interaction measurements have been carried out by utilizing the torque and drag force on two paddlewheel satellites with perigee altitudes between 250 and 300 km. The angular distribution of the re-emitted molecules was inferred to be nearly diffuse, and the accommodation coefficients were between 0.65 and 0.9. A proposed satellite experiment, Project ODYSSEY, is described in which the surface-particle-interaction and atmospheric parameters will be measured with much improved accuracy.

1. Introduction

Approximately a dozen paddlewheel satellites have been sent into orbit in the past 10 years. They have been designed to study the magnetosphere and the solar wind. It is only by accident that they have revealed information about the interaction of air molecules with satellite surfaces. At first, the aerodynamic interaction was regarded as a nuisance. Afterwards, it was realized that this interaction could provide information about surface-particle interactions which had hitherto been unavailable.

The designers of the first paddlewheel satellite, Explorer VI, expected the momentum of the air molecules re-emitted by the satellite surfaces to be described by Maxwell's classical model(1), with approximately 95% of the molecules diffusely reflected(2). A postflight analysis(3) revealed

16

that the spin had decayed three times as fast as expected, and an order of magnitude faster than would have occurred if the re-emission had been completely diffuse and accommodated. The Explorer VI results remained unpublished, so designers continued to underestimate the aerodynamic torques on paddlewheel satellites. This caused difficulties for Ariel II, many of whose experiments became inoperative after 3 months because of the rapid decay of the spin, and the consequent attitude drift(4,5).

Since Ariel II, higher perigee altitudes have been used for paddlewheel satellites, thus reducing the aerodynamic torques. Of more direct interest to this symposium, the effects of aerodynamic torques on paddlewheel satellites have been studied by several authors(3,4,6-11). These studies have revealed information about gas-surface interactions in the space environment which cannot at present be obtained by simulation studies in the laboratory.

2. The Results of Measurements Using Paddlewheel Satellites

Paddlewheel satellites reveal information on gas-surface interactions which conventional satellites do not: The reason is that conventional satellites furnish a single aerodynamic measurement, which is proportional to the product of the air density and the drag coefficient, while paddlewheel satellites furnish two measurements, one of which is very sensitive to the incident momentum, and the other is most sensitive to the re-emitted momentum. The first measurement, the aerodynamic drag, is well known, and has been extensively treated in the literature(12-16). The second kind of measurement, the aerodynamic torque, is little known although it has been studied by several workers(2-4,6-11,17). The simplest analysis of the effect of aerodynamic torque on a paddlewheel satellite is the original analysis of Leon and Reiter(2), which was based on Maxwell's classical model(1) of gas-surface interaction. Leon and Reiter's analysis is summarized in the Appendix. A more general analysis based on Schamberg's models of gas-surface interaction(18) appears in Reference (10). The analysis based on the diffuse case of Schamberg's models has been worked out in great detail in Reference (9).

Whenever a new method of measurement is used, it is natural

to ask how its results compare with older, better established methods. In the measurement of aerodynamic torques, one might wonder whether solar radiation torque had been correctly subtracted out, and whether charge drag or some other exotic effect could have invalidated the measurements. Fortunately, both the drag and the torque are proportional to the air density, so direct comparisons can be made between the two types of measurement.

Three such comparisons have been made: (1) Densities at 278 km given by the CIRA 1965 model atmosphere[19] have been compared with those measured by the spin decay of Explorer VI[10]; (2) The corpuscular heating effect derived from the spin measurements of Explorer VI[20] has been checked against two curves for this effect obtained from satellite drag data by Jacchia and his colleagues[21,22]; (3) Density scale heights measured by the paddlewheel satellites Explorer VI and IMP II have been compared with scale heights obtained from drag data[23]. The good agreement found in all three cases gives us confidence that the method is accurate.

Although the drag force and torque on paddlewheel satellites can be accurately measured, this does not guarantee that the drag coefficient (C_d) and accommodation coefficient (AC) can be found. A model of surface particle interaction must be assumed before these quantities can be computed. In order to determine the range of possible AC's and C_d's, five different models were used with the Explorer VI and Ariel II data: Maxwell's classical model[1], two cases of Schamberg's model[18], and two cases based on angular distributions observed by Alcalay and Knuth[24] at 1 e.v. Polar plots of the angular distributions of re-emitted molecules are shown in Fig. 1. All the cases except Maxwell's were computed using the mechanics of Schamberg's models, so that the speed of re-emission is assumed to be independent of the angle of reflection. The angular distributions of molecular flux and momentum are identical in this formulation, which causes the energy AC to be simply related to the speed of incident and reflected molecules. The equations for calculating C_d and AC from paddlewheel satellite data have already been published[10], so they will not be repeated here.

The AC's computed for the first month Explorer VI was in orbit[10], and for the first 5 days of Ariel II[11] are shown in Fig. 2. Each paddlewheel satellite had two surface mate-

rials, which were assumed to have the same AC. Regardless of the angular distribution assumed, the AC is high. This result has several implications: (1) The angular distribution of reflected molecules is nearly diffuse; (2) The satellite surfaces are contaminated.

These conclusions fit in with other experimental facts: We know that satellite surfaces are contaminated by adsorbed atmospheric gases because the nude mass spectrometer on Explorer XVII continued to measure sizable concentrations of atmospheric gases during the part of its spin cycle in which the ionizing source was completely shielded from the incident air stream(25). In laboratory measurements on argon at 4 e.v.(26), nearly diffuse reflection from contaminated surfaces was observed when the background pressure corresponded to an altitude of 170 km in the atmosphere.

The three satellites mentioned in the preceding paragraphs had perigee altitudes between 250 and 300 km. For that range of altitudes, the results above suggest that satellite surfaces are contaminated, the angular distributions are nearly diffuse, and the AC's are between 0.65 and 0.9. The C_d's implied by these measurements are about 2.25 for Ariel II, which was in a moderately eccentric orbit, and 2.4 for Explorer VI which was in a highly eccentric orbit(11)

Thus it appears that the C_d of 2.2 which is conventionally used to derive atmospheric densities from satellite orbital decay(27) is close to the actual value for the satellites in orbits of low or moderate eccentricity which usually are used. However, the surface contamination is a function of the ambient pressure, so this conclusion only applies to perigee altitudes below 300 km. A satellite with a perigee height of 700 km might have a C_d that was considerably higher or lower, depending on the AC, the angular distribution of re-emitted momentum, and the satellite geometry.

Laboratory measurements(26,28,29) and theoretical calculations(30-32) indicate that the AC's of contaminated surfaces do not depend greatly on the substrate material, especially at the higher incident energies. We cannot say from the satellite experiments how much the AC depends on the substrate material, the level of contamination, or the angle of incidence. The effect of angle of incidence could be investigated by using some data from Ariel II which exist for many angles of incidence, but which have remained largely unreduced because of lack of time and money. Unused

data also exist for several other satellites. Most of these uncertainties, however, will remain with us until satellite experiments are conducted with the specific purpose of investigating gas-surface interactions in the space environment.

3. Project ODYSSEY

Because of the incompleteness and lack of coordination of the measurements of air density, composition and surface-particle interaction which have so far been performed in space, the Marshall Space Flight Center has proposed the ODYSSEY Program[33,34], which will perform a coordinated set of measurements on several satellites simultaneously launched into neighboring orbits. The part of this program devoted to surface-particle-interaction measurements in the free-molecular regime will now be described.

One satellite will be a diffusely reflecting sphere, a type of satellite which was first suggested by Schaaf[35]. Its C_d can be accurately calculated from the speed ratio and the satellite temperature. STADAN tracking measurements of its orbital decay will measure the drag force. This will enable the average atmospheric density over 3-day intervals to be determined within 1 or 2 percent.

The second satellite will be a paddlewheel satellite. Its C_d will be directly calculable from its orbital decay, because the atmospheric density will be known from the diffusely reflecting sphere. Knowing the absolute atmospheric density from the sphere, and the satellite velocity from the tracking data, we shall know the momentum imparted to the paddlewheel satellite by incident air molecules. The rates of orbital decay and spin decay of the paddlewheel satellite can then be used to calculate components of the momentum of the re-emitted molecules.

In order to measure the momentum re-emitted from several different materials, the central body of the paddlewheel satellite will be coated with paint (whose principal function is to control the temperature inside the satellite), and the two sides of the paddles will be of two other materials, such as silicon dioxide and gold. The paddles will be movable like a variable pitch propeller, so that the effect of angle of incidence on the surface interaction parameters can be measured, and the drag on the painted sphere

can be separately measured. By subtraction, the force components on single materials can be found.

It is the force components which we measure, but we would also like to know whether some simple model gives a good macroscopic representation of the interaction of air molecules with satellite surfaces. It is planned to compare the measured momentum components with those given by Maxwell's and Schamberg's models, and superpositions of Schamberg's models with different AC's. Extrapolation of results of the analysis of Explorer VI and Ariel II suggests that AC's can be measured with an accuracy of a few percent every 3 days. Suitable equations for making most of these calculations have been published in connection with work on earlier paddlewheel satellites[2,10]. The physics of the problem is made clear in the Appendix, which is a summary of Reference (2).

Even with all these quantities being measured, it is possible that the measurements would not apply to any other satellite: Adsorption and desorption proceed continuously, so C_d probably changes continuously in the neighborhood of perigee. A satellite with a different perigee height or orbital eccentricity might have a different average C_d near perigee. In order to detect such effects, the satellites will be placed in highly eccentric orbits. Lunar and solar gravitational perturbations will then raise and lower the perigee altitude with periods of 14 days and 6 months, respectively. C_d can be measured for many different perigee heights. If the sun sensor which measures the spin rate is sufficiently accurate (10 sec of arc), it should even be possible to detect changes in the drag coefficient as the satellite passes down through perigee and back up.

Several different investigators will make simultaneous measurements of the atmospheric density, temperature, and composition by the mass spectrometric[36] and extinction[37] techniques. It is hoped that a nude mass spectrometer will be able to correlate the level of surface contamination with the AC at various perigee altitudes between 110 and 300 km. (The use of mass spectrometers to study adsorption is discussed in a companion paper[38].) The level of solar UV radiation will also be measured in several energy ranges. One experiment often illuminates some point which is

obscure in another experiment, so it is hoped that by performing all these experiments at the same place and time, the present disagreements[39,40] among satellite density and composition measurements will be resolved.

4. Conclusions

Measurements made by paddlewheel satellites and mass spectrometers in the altitude range 250 to 300 km indicate that satellite surfaces at these altitudes are contaminated with adsorbed atmospheric gases, the AC's are in the range 0.65 to 0.9, and (by implication) the angular distribution of re-emission is nearly diffuse. The C_d's implied by these measurements are 2.25 for Ariel II, which was in a moderately eccentric orbit, and 2.4 for Explorer VI, which was in a highly eccentric orbit. This appears to confirm the C_d of 2.2 which is conventionally used to reduce satellite drag data. However, the AC, C_d, and angular distribution could vary with altitude, orbital eccentricity, angle of incidence, and surface material, so the air densities inferred from past drag measurements could contain sizable errors, especially if perigee were above 600 km.

To eliminate the deficiency of knowledge in these areas, the Marshall Space Flight Center has proposed Project ODYSSEY. In this project, many different investigators will make coordinated measurements of AC's, C_d's, satellite surface contamination, atmospheric density, composition, and temperature at many different altitudes, as well as the solar UV energy source. The many techniques which will be employed simultaneously make this the most detailed study of the upper atmosphere and its interaction with satellites which has yet been proposed. It is hoped that this concerted investigation will reveal how satellites interact with the atmosphere, and will resolve present disagreements among density and composition measurements made by different methods.

ACKNOWLEDGMENTS

We acknowledge the major contribution of Dr. H. I. Leon to the understanding of aerodynamic torques. We appreciate the advice and assistance of Professor E. L. Knuth in preparing the original proposal to include a paddlewheel satellite in Project ODYSSEY. We attest to the vision displayed

by Mr. J. O. Ballance and his colleagues at the Marshall Space Flight Center in planning and organizing the ODYSSEY Project. We thank TRW Systems, the Goddard Space Flight Center, the Royal Meteorological Office, and their personnel for releasing unpublished paddlewheel satellite data and internal reports. The original analysis of the aerodynamic torques on a paddlewheel satellite was supported by the United States Air Force in connection with the Explorer VI program. The writing of this paper was partly supported by the Douglas Aircraft Company Independent Research and Development Program.

APPENDIX

Leon and Reiter's Analysis of the Aerodynamic Torques on a Paddlewheel Satellite

Paddlewheel satellites are injected into orbit so that the spin axis nearly coincides with the velocity vector at perigee. The satellite spins like a four-bladed propeller, with the incident air molecules continuously striking one side of the paddles. The resulting torque increases or decreases the spin rate during each perigee passage, depending on the orientation of the paddles.

Leon and Reiter's[2] original analysis is summarized here, because it clearly illustrates the physics of the problem, without the geometrical complications of a more detailed analysis[9]. The velocity vector at perigee is assumed to coincide exactly with the spin axis, so that scalar equations can be used. Maxwell's original model of surface-particle interaction is employed, so a fraction σ of the incident molecules initially stick on the paddles, then are perfectly accommodated and diffusely re-emitted, while a fraction $1-\sigma$ are specularly reflected.

The model of the satellite used in Leon and Reiter's analysis is shown in Figure 3. In this figure, the velocity of the satellite is V, the instantaneous velocity of a paddle relative to the center of mass is ωL, and the angle between the satellite velocity vector and the paddle normals is θ. The rate at which mass strikes each paddle is $\rho V \times A \cos \theta$, where ρ is the air density and A is the total area of one side of a paddle. The drag force caused by the

fraction, σ, of particles temporarily sticking on each paddle is

$$F_i = -\sigma\rho VA \cos\theta\, V \tag{1}$$

There is only a small component of F_1 acting to retard the spin, F_1 ($\omega L/V$). The torque caused by air molecules striking the four paddles and sticking is then

$$\tau_1 = -4\, \sigma\rho VA\omega L^2 \cos\theta \tag{2}$$

The torque caused by diffuse re-emission is calculated by beginning with the assumption that the rate at which mass is re-emitted equals the rate at which it sticks:

$$dm_2/dt = 4\, \sigma\rho VA \cos\theta \tag{3}$$

The torque caused by diffuse re-emission is then

$$\tau_2 = -4\, \sigma\rho VA \cos\theta C_n L \sin\theta \tag{4}$$

where C_n is the normal component of the velocity of re-emission. The total torque caused by molecules which stick and then are diffusely re-emitted at the surface temperature is

$$\tau_d = -4\, \sigma\rho VA \cos\theta\, L^2\, [\omega + C_n \sin\theta/L]. \tag{5}$$

The mass rate for the specularly reflected particles is

$$dm_s/dt = 4\, (1 - \sigma)\, \rho VA \cos\theta \tag{6}$$

The force is normal to the paddles, and equal to

$$F_s = -4\, (1 - \sigma)\, \rho VA \cos\theta\, 2\, V \cos\theta \tag{7}$$

The torque caused by the specularly reflected molecules is then

$$\tau_s = -4\, (1 - \sigma)\, \rho VA \cos\theta\, 2\, V \cos\theta\, L \sin\theta \tag{8}$$

Combining the torques caused by the particles which are diffusely and specularly re-emitted (given by equations (5) and (8), respectively), the equation of motion for the

spin becomes

$$I\dot{\omega} = -4\,\sigma\rho V A L^2 \cos\theta\,\{\omega + \frac{C_n \sin\theta}{L} + \frac{2(1-\sigma) V \cos\theta \sin\theta}{\sigma L}\} \qquad (9)$$

where I is the roll moment of inertia, and ω is the angular velocity of spin.

REFERENCES

1. Maxwell, J. C., Scientific Papers, Dover, N. Y., 2, 708, 1951.

2. Leon, H. I., and Reiter, G. S., "Effect of Aerodynamic Moments on Spin Rate," TRW Systems, GM59-8021, 2-54 (1959).

3. Reiter, G. S., "Free Molecule Flow and Particle-Surface Interactions," (Unpublished), p. 31.

4. Anon., Ariel II Engr. Data Analysis, Phase III (Final) Rept. Westinghouse Elect. Corp., Baltimore, 1965.

5. Stewart, K. H., and Miller, D. E., Preliminary Results from Ozone Expts. in the Ariel II Satellite (unpublished).

6. Alexander, J. H., Bowen, P. J., Henderson, C. L., and Willmore, A. P., Aspect History and Spin-Rate Analysis (of Ariel I), (unpublished).

7. Blanchard, D., Unpublished Calculations on Ariel II.

8. Meyerson, H., Some Preliminary Engineering Data from the Explorer XXVI (EPE-D) Satellite (unpublished).

9. Moe, K., "Atmospheric Densities Determined from the Spin Decay of Explorer VI," Thesis, University of California, Los Angeles, 1966. (University Microfilms order No. 66-9319.)

10. Moe, K., Planet. Space Sci., 14, 1065, 1966.

11. Moe, K., "Recent Experimental Evidence Bearing on Satellite Drag Coefficients," Douglas Paper 5176, to be published in the AIAA J. about July, 1968.

12. Schaaf, S. A., and P. L. Chambré, in Fundamentals of Gas Dynamics, H. W. Emmons (Ed.), Princeton U. Press, 1958.

13. Masson, J. D. (Compiler) Aerodynamics of the Upper Atmosphere, Rept. R-339, RAND Corp., Santa Monica, Calif., 1959.

14. Sterne, T. E., ARS J., 29, 777, 1959.

15. Wolverton, R. W. (Ed.), Flight Performance Handbook for Orbital Operations, Wiley, N. Y., 2-360, 1963.

16. King-Hele, D. G., Theory of Satellite Orbits in an Atmosphere, Butterworths, London, 1964.

17. Warwick, J. W., Decay of Spin in Sputnik I, Planet. Space Sci., 1, 43, 1959.

18. Schamberg, R., "A New Analytic Representation," RM-2313, The RAND Corp., Santa Monica, Calif., 1959.

19. COSPAR Working Group IV, COSPAR International Reference Atmosphere, 1965 (CIRA, 1965), North Holland Publishing Co., Amsterdam, 1965.

20. Moe, K., Planet. Space Sci., 15, 1821, 1967.

21. Jacchia, L. G., Smithsonian Astrophys. Obs. Sp. Rept. No. 170, 1964.

22. Jacchia, L. G., Slowey, J., and Verniani, F., Smithsonian Astrophys. Obs. Sp. Rept. No. 218, 1966.

23. Moe, K., Klein, D., Maled, G., and Tsang, L., "Density Scale Heights at Sunspot Maximum and Minimum from Satellite Data," Douglas Paper 4778, to be published in Planet. Space Sci. about April, 1968.

24. Alcalay, J. A., and Knuth, E. L., Proc. 5th Rar. Gas Dyn. Symp., Academic Press 1, 253, 1967.

25. Reber, C. and Nicolet, M., Planet. Space Sci., 13, 621, 1965.

26. Abuaf, N. and Marsden, D. G. H., Proc. 5th Rar. Gas Dyn. Symp., Academic Press, N. Y., 1, 199, 1967.

27. Cook, G. E., Annales de Geophysique, 22, 53, 1966.

28. Wachman, H. Y., ARS J., 32, 2, 1962.

29. Kaminsky, M., Atomic and Ionic Impact Phenomena, Springer, Berlin, 1-98, 1965.

30. Shin, H., J. Chem. Phys., 42, 3442, 1965.

31. Allen, R. T. and Feuer, P., J. Chem. Phys., 43, 4500, 1965.

32. Oman, R. A., AIAA J., 5, 1280, 1967.

33. Anon., ODYSSEY Preliminary Program Proposal, NASA Marshall Space Flight Center, September 1968.

34. Youngblood, W. W., and Walters, W. P., in Proc. 3rd Natl. Conf. Aerospace Meteorology, Am. Met. Society, Boston, 1968.

35. Schaaf, S. A., in Masson, J. D. (Compiler), Aerodynamics of the Upper Atmosphere, Report R-339, RAND Corp., Santa Monica, Calif., 1959.

36. Nier, A. O., Mass Spectroscopy, 15, 67, 1967.

37. Hall, L. A., Schweizer, W., and Hinteregger, H. E., J. Geophys. Res., 70, 105, 1965.

38. Moe, M. M., and Moe, K., "The Roles of Kinetic Theory and Gas-Surface Interactions in Measurements of Upper-Atmospheric Density," Douglas Paper 5064 (this symposium).

39. Newton, G. P., Horowitz, R., and Priester, W., Planet. Space Sci., 13, 599, 1965.

40. Cook, G. E., Phil. Trans. Roy. Soc. (London), A, 262, 172, 1967.

FIGURES

FIGURE 1. THE MODELS OF ANGULAR DISTRIBUTION

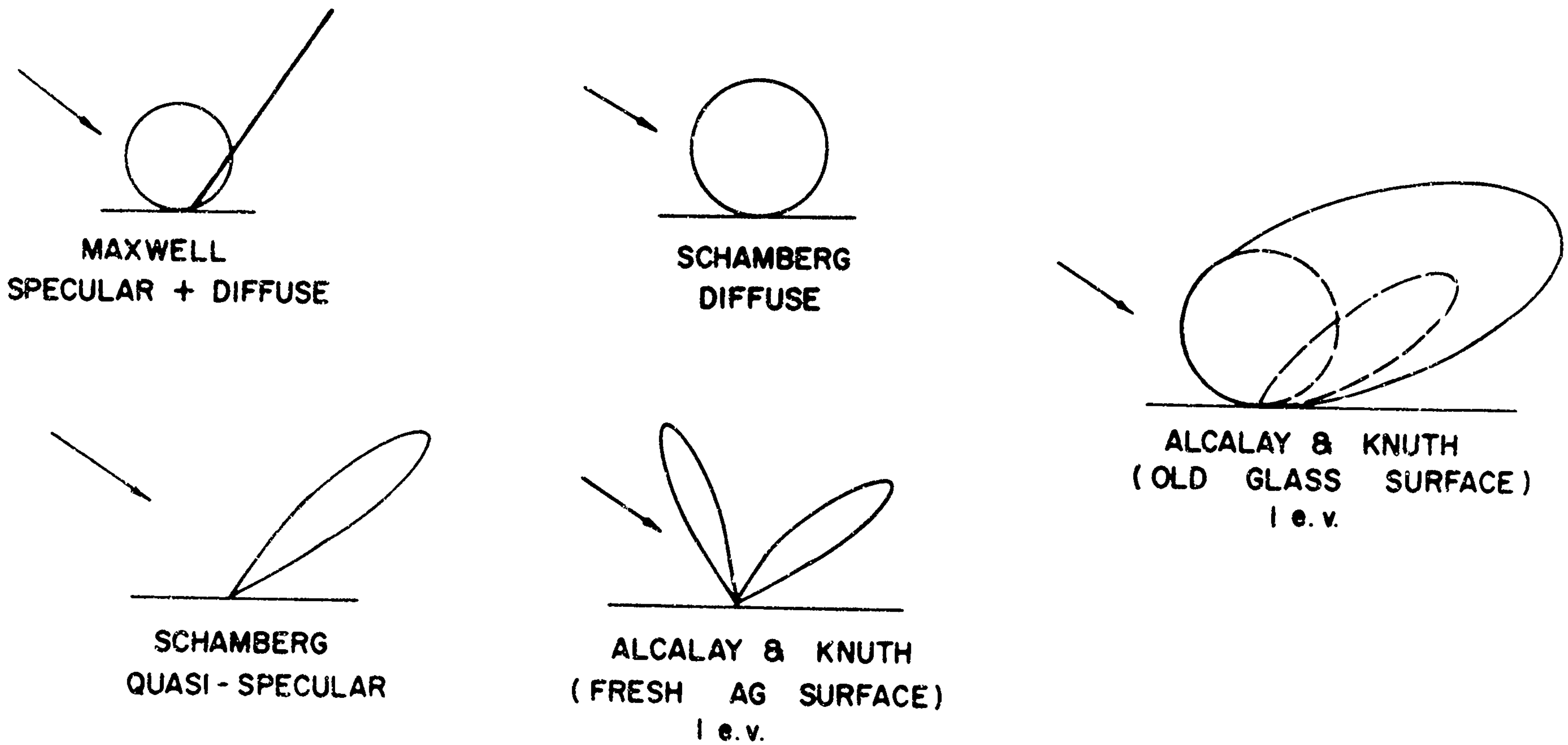

FIGURE 2. ACCOMMODATION COEFFICIENT AS A FUNCTION OF THE ASSUMED ANGULAR DISTRIBUTION

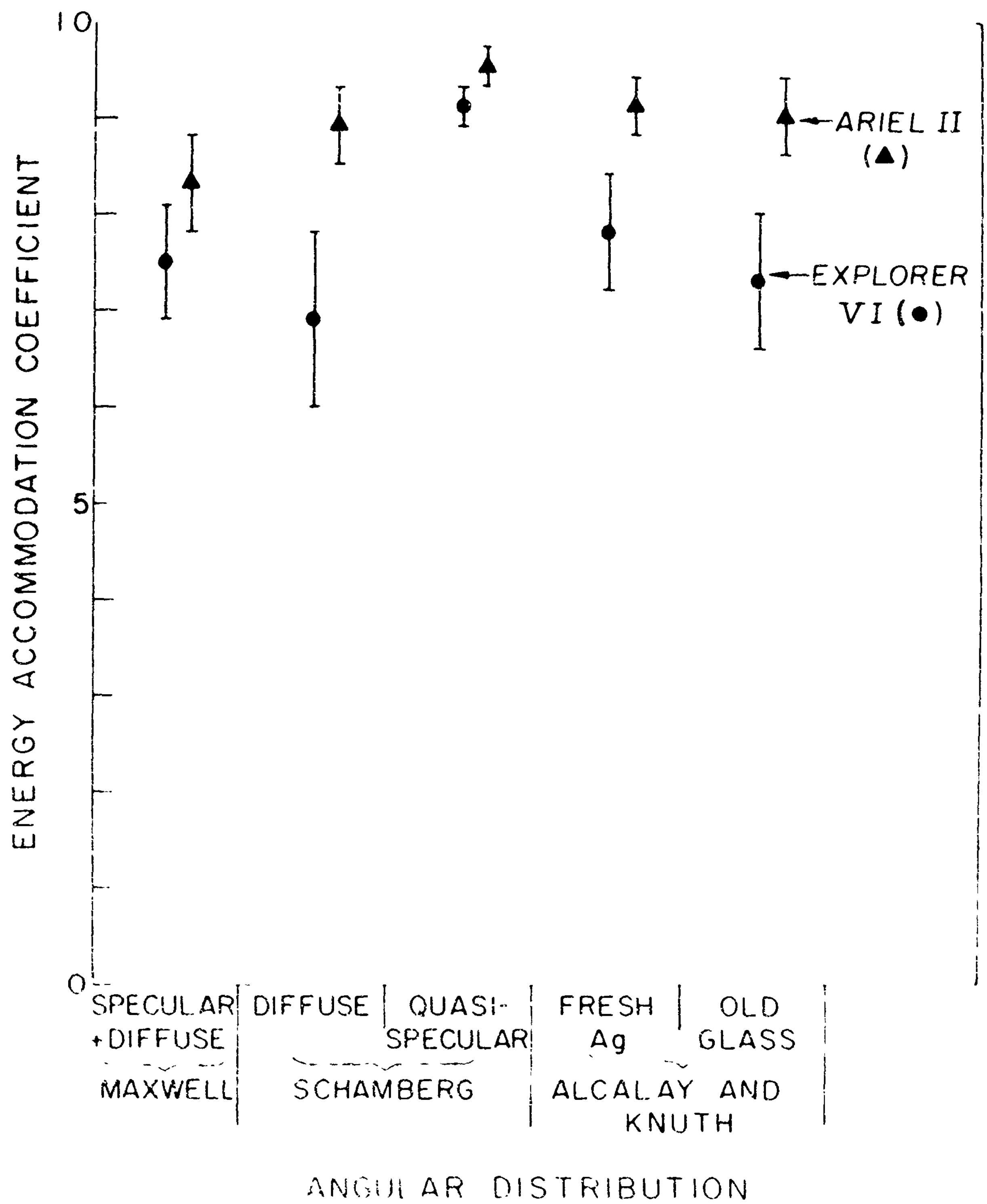

FIGURE 3. EXPLORER VI SATELLITE AT PERIGEE
(AFTER LEON AND REITER)